Section 6

Adaptive Signal Control Strategies

This section evaluates the potential benefits of adaptive traffic signals in a test grid network and a typical downtown urban setting. The study used the THOREAU and INTEGRATION traffic simulation models.

6.1 Background

Traffic signals are an important component of traffic management in urban and suburban areas. When two arterials cross, the throughput capacity of each arterial is significantly reduced, since the traffic flow on each must be interrupted periodically to service the cross-direction flow. Traffic engineers around the world are studying and prototyping various concepts for operating traffic signals more efficiently by using detectors and real-time control systems. These concepts are called “adaptive” because the signals adapt to actual traffic conditions rather than operating on a fixed timing plan. Adaptive signal systems are part of ATMS, a fundamental component of ITS.

The lTS architecture developed to date is flexible with respect to ATMS and does not prescribe specific traffic control schemes or algorithms for implementation. Therefore the analyses of the benefits of ATMS were based on generic ATMS schemes that could be supported by the ITS architecture. These schemes are simpler than would be deployed in actual systems, and therefore should represent conservative estimates of ATMS benefits.

THOREAU is a microscopic simulation of vehicle movement through a network. It models the details of vehicle car-following, acceleration and deceleration, lane-changing, turning movements, incident avoidance, and queue formation and dissipation. INTEGRATION is a mesoscopic model, tracking individual vehicles, but using flow equations and a queuing model to model the travel time on each link. Vehicles do not accelerate or decelerate at traffic signals; they start and stop instantly.

6.2 Hypothesis

The study of the potential benefits of ATMS began with the following hypothesis concerning the benefits of adaptive signals compared to signals with fixed timing plans:

If traffic generally follows a predictable pattern and a set of fixed signal timing plans is developed to optimize the flow of traffic given the predictable demand, the benefits of adaptive traffic signals will be small. However, the more traffic deviates from expected levels, either in total volume or in the direction of traffic flow, the greater will be the value of adaptive traffic signals.

The next section describes the modeled signal strategies and the sections after that describe the networks and demand scenarios used to test the hypothesis for a typical urban setting.

4.3 Types of Signal Control Modeled

This section describes fixed timing plans and two methods of adaptive signal control as they are implemented in the THOREAU and INTEGRATION models. The third adaptive method, signal actuation, is implemented only in THOREAU.

6.3.1 Fixed Signal Timing Plans

The base case for signalized traffic control is the fixed timing plan. Each signal simply repeats its fixed cycle continually throughout the simulation. Signal timing plans may be derived from a program that optimizes signal plans for a given traffic load, such as TRANSYT-7F (FHWA, 1986). In a well-designed timing plan, the phase splits are proportional to the expected volumes of traffic from each direction, and signals may be synchronized to provide corridor progression (a "green wave") along selected corridors. Mitretek developed a "good" fixed timing plan for each of the networks used for this study.

6.3.2 Webster-Cobbe Isolated Signal Optimization

The first strategy for adaptive signal timing uses a heuristic algorithm for optimizing individual signals based on the static-optimal Webster-Cobbe algorithm (Webster and Cobbe, 1966). This strategy is designated by ' WCI' in the simulation results presented in this paper. Detectors are placed at a specified distance upstream from each intersection to count the traffic in each lane on each approach. At the end of periodic intervals - typically five to ten minutes - the algorithm optimizes each signal's timing plan, using the traffic counts for two purposes. First, it determines the optimal cycle length as a function of the total traffic and the signal lost time (yellow and red interval times). In general, when the volume-to-capacity (V/C) ratio of the intersection is high, longer cycle lengths are more efficient (minimizing lost time due to phase changes). Shorter cycle lengths are more efficient when the intersection V/C ratio is low (minimizing time when the light is green but no one is there to take advantage of it). Secondly, the algorithm computes the length of the green phase in each direction in proportion to the level of observed traffic coming from the direction. Optimization is done independently for each signal. The algorithm does not work well when intersection V/C ratios are greater than one, indicating gridlock conditions.

In THOREAU, when a new signal plan is determined, it does not take effect until the cycle in progress has been completed. In INTEGRATION, the new plan takes effect immediately. In this study, the ATMS update interval was set to six minutes. The cycle length determined by the optimization algorithm was constrained to lie between 30 seconds and 180 seconds. In THOREAU the detectors were placed 30 m (100 ft.) upstream from each intersection; in INTEGRATION they were placed at the intersection stop bar.

6.3.3 Dynamic Corridor Optimization

The second strategy for adaptive signal timing, called Dynamic Corridor Optimization (DCO), was developed at Mitretek. A corridor consists of an ordered sequence of links. Two corridors ate used to define parallel traffic in opposing directions. If all the signal controllers within a corridor are synchronized to a common cycle time, a progressive green wave can be maintained. A signal controller may belong to several corridors, but green waves can only be maintained on one or two of the corridors to which the signal controller belongs.

THOREAU computes a corridor congestion index (CCI) for each corridor at the beginning of every corridor optimization cycle to determine the corridor with the worst congestion. The CC1 is computed as a weighted sum of: (1) the corridor delay (end-to-end corridor travel time minus freeflow time); (2) the average queue length at intersections; (3) the average stop time at intersections; and (4) the weighted sum of intersection V/C ratios along the corridor. For this study, the corridor optimization routine was invoked every ten minutes.

Two variations of the DCO strategy were tested using THOREAU. For the first variation, labeled "DCOl" in the simulation results, the weights on the four components of the CCI were (0.2, 0.3, 0.3, 0.2). In the second variation, labeled "DCO2", the weights were (0.0, 0.0, 0.0, l.0) (i.e., only the intersection V/C ratios were used). The first variation relies on vehicle probes to obtain stop time and trip delay information, whereas the second variation only requires traffic counts that can be obtained with common loop detectors.

Once the corridor with the highest CCI is determined, the node with the highest V/C ratio in that corridor is called the bottleneck node. The Webster-Cobbe algorithm is called to determine a new cycle time for the bottleneck node. The remaining controllers in the corridor are assigned the same cycle time, but their phase splits are computed separately to serve individual intersections most efficiently. The offset of each controller along the corridor is set to achieve a progressive green wave, assuming that vehicles will travel at freeflow speeds between intersections.

The corridor optimization procedure is repeated for the remaining corridors. If the next most congested corridor does not intersect any previously optimized corridors, it may be optimized independently. If it has one intersection in common with a previously optimized corridor, it may be optimized using the same cycle length as the previous corridor and using the offset of the common intersection as a fixed point. If it has more than one intersection in common with previously optimized corridors, it cannot be optimized. When this procedure is finished, the remaining corridor fragments or isolated intersections are optimized in isolated mode using the Webster-Cobbe algorithm. THOREAU and INTEGRATION have the ability to specify different corridor priorities, but that capability was not used in this study.

When a new set of synchronized signal plans is determined, THOREAU phases them in over one or two cycles so as to minimize disruption at the intersections. INTEGRATION implements the new plans immediately.

6.3.4 Actuated Signal Control

THOREAU models fully actuated controllers by creating upstream and stopbar detectors on all lanes of each intersection approach to track the intersection queue lengths. Each approach is assigned a minimum, maximum, and incremental green interval. The approach is given a green signal of minimum length that may be extended by increments up to the maximum green period if the number of actuations or the queue length for that approach exceeds the number of vehicles waiting for the cross approach. If the maximum green time is reached before all traffic clears the intersection, the queue of remaining traffic will hasten the return of green to that approach. Phase transition is preceded with preset yellow and all-red clearance.

THOREAU also models semi-actuated controllers, with detectors only on the minor approaches. The signal stays green for the major approaches until traffic is detected on a minor approach. Then the light turns green for the minor approach for a minimum period that may be extended up to a maximum time if there is further actuation on a minor approach. This study placed semi-actuated controllers where there was a clear distinction between major and minor approaches and fully actuated controllers elsewhere.

6.4 Description of the Urbansville Scenario

This section describes the Urbansville network, five traffic scenarios, the two fixed signal plans used for the Urbansville study, and the study methodology. The INTEGRATION model was not used with the Urbansville scenario. The Urbansville network and results have been previously documented by Glassco (1996). Additional Urbansville scenarios and results, obtained after the draft release of this report, are found in section 6.6.

6.4.1 Description of the Test Network

The Urbansville network, based on the roads and traffic signals found in downtown and suburban Detroit, Michigan, was selected for the lTS Architecture Development project to represent an urban area. The test network used in this ATMS study is a subset of Urbansville, representing Detroit's downtown Commercial Business District, so it is called "Urbansville CBD." It includes the area bounded by Warren Avenue on the north, Jefferson Avenue on the south, Cass Avenue on the west, and Brush Street on the east. It is approximately 3.7 km (2.3 mi.) in the north-south direction and 1 km (0.6 mi.) in the east-west direction.

Figure 6-l depicts the 398 links (streets) and 182 nodes (intersections) in Urbansville CBD. Double lines represent two-way streets and single lines represent one-way streets. The thick lines with arrows represent corridors synchronized by Mitretek's fixed timing plan (see section 6.4.3). The circled nodes are origins and destinations (O-D nodes) of traffic streams. Most O-D nodes appear on the edges of the network, but some lie in the interior. Most (132) of the non-circled intersections have traffic signals. The method of operation of these signals is the major control variable of this study. The remaining intersections have 2-way or 4-way stop signs.

The network is not an exact representation of Detroit's CBD. Some small streets have been omitted and some streets modeled as one-way are actually two-way. All streets are modeled with two lanes. These changes enabled the network to be loaded to near-capacity levels without exceeding the maximum number of vehicles the model can track simultaneously or significantly increasing run times. Fisher Freeway is not modeled because it does not interact with the rest of the arterial streets modeled, but the eastbound and westbound Fisher Freeway Service Drives are modeled.

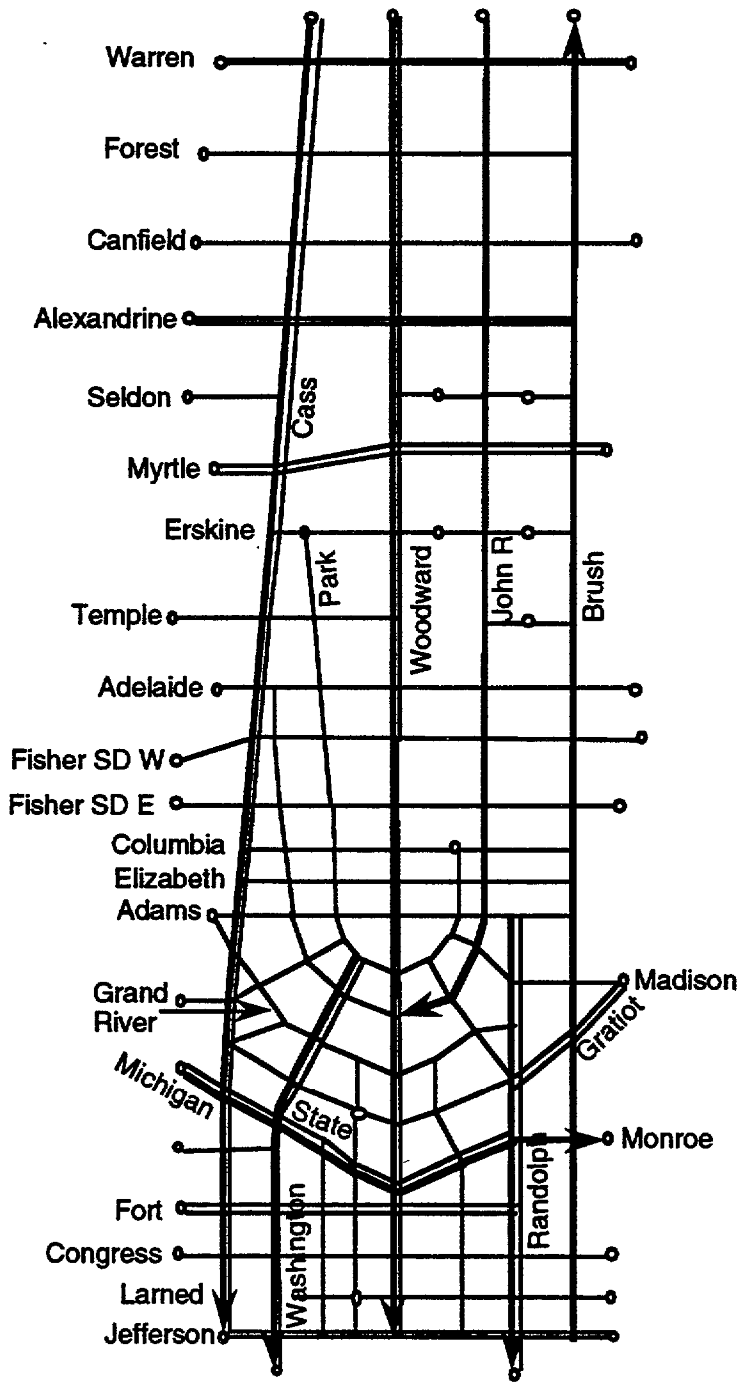

Figure 6-1. Urbansville CBD Network

6.4.2 Description of Traffic Scenarios

There are 46 paths through the network, beginning and ending at O-D nodes. Each traffic scenario is defined by specifying the hourly traffic volume for each path. Throughout the simulation, vehicles are generated on each path. The interarrival time between vehicles on each path is a random variable drawn from an exponential distribution, with the average interarrival time inversely proportional to the path's specified traffic volume. Each vehicle follows its path from origin to destination, records its trip tune, and disappears. Deviations from paths resulting from route guidance were not modeled in this study.

Five traffic scenarios represent various levels and directions of traffic on the streets of Urbansville CBD. They ate described as follows:

1 The Base scenario represents the morning rush hour period, with traffic predominantly in the southbound direction. The traffic flow modeled along each path is not based on actual traffic counts, but was designed to produce a V/C ratio of 0.5 or greater on many major links and to produce several intersections with V/C ratios of over 0.75. An intersection V/C ratio is computed as the sum of the V/C ratio of the busiest north-south approach and the V/C ratio of the busiest east-west approach

2. The Light Traffic scenario has the same traffic pattern as the Base scenario, but with traffic volumes on all paths (and thus all links) reduced by 40 percent.

3. The Heavy Traffic scenario has the same traffic pattern as the Base scenario, but with traffic volumes on all paths (and thus all links) increased by 20 percent.

4. In the Alternate scenario, traffic volumes are increased for paths that are predominantly northbound, eastbound, and westbound, and decreased by the same amount for paths that are predominantly southbound. The total number of vehicles is the same as in the first scenario.

5. In the Transition scenario, the arrival rate on each path begins the same as the Base scenario, but transitions continuously toward the arrival rates of the Alternate scenario, arriving at those rates by the end of the simulation.

The major streets, total length, freeflow tune, and traffic volume are presented for a sample set of paths in table 6-1. The last two columns show the hourly traffic volumes for the Base and Alternate scenarios. The volumes for the Light and Heavy Traffic scenarios are 40 percent less and 20 percent greater than the Base volumes, respectively. The volumes for the Transition scenario are interpolated between the Base and the Alternate volumes.

The most significant difference between the Base and Alternate scenarios lies in volume of traffic on synchronized corridors. For the Base scenario, 47 percent of the traffic is on links where the signal at the end is timed to allow a smooth progression of vehicles from the upstream intersection. For the Alternate scenario, only 29 percent of the traffic is on these links. The Alternate scenario represents the situation where an unexpected or atypical event such as weather, an incident, or large public gathering causes the traffic pattern during rush hour to deviate significantly from normal.

Table 6-1. Sample Path Statistics

#	Street(s)	Length (mi.)	Freeflow Time (sec.)	Base Volume (veh./hr.)	Alternate Volume (veh./hr.)
1	Cass S/ Congress W	2.3	273	514	277
2	Cass S/Michigan W	1.9	231	514	277
3	Woodward S/ Jefferson W	2.5	303	600	277
4	Seldon W John R /Elizabeth W	.9	114	514	277
5	John R/Woodward S/ Jefferson	2.6	317	514	277
6	Warren W John R/ Randolph S	2.5	300	514	277
7	Park S/Washington S	1.4	171	514	277
8	Woodward S/Fisher E	1.8	213	514	277
9	Fisher E/Elizabeth E/Randolph S	1.3	161	450	277
10	Grand/ Farmer/ Randolph S	1.0	120	400	277
11	Adams E/ Park S/Washington S	.9	110	400	300
12	Adelaide E/Woodward S/ Larned	1.5	180	450	277
13	Warren E	.6	68	450	450
14	Forest E/ Brush/ Warren E	.8	90	400	450
15	Myrtle E	.6	67	360	450

All scenarios consist of traffic on each path arriving at random intervals with average interarrival times corresponding to the hourly traffic volumes listed in table 6-1. Vehicles begin arriving at simulation time zero and stop arriving at simulation time 30 minutes. The total simulation time is one hour.

6.4.3 Fixed Signal Plans

The signal plan named "Base Fixed Plan" is based on the actual set of signal timing plans for the Detroit CBD, except that left turn arrows were not modeled. All the signal cycle lengths are 70 seconds. The length of each yellow interval is four seconds and the length of the all-red clearing interval is one second. The 60 seconds of green time is split either 30/30 or 35/25, with 35 seconds given to the approach with the heavier traffic. Signals are synchronized along Woodward Avenue for the southbound direction, but no other signals are synchronized.

As will be seen in the next section, this signal timing plan performed poorly in all scenarios. The results do not imply that the actual signals in Detroit are timed badly. Traffic volumes for the scenarios are artificial and numerous streets and intersections were modified. The intent was to represent a non-optimized fixed timing plan found in many urban areas today - one that has not been extensively synchronized or else has not been updated in several years, so that traffic patterns and volumes have changed from those for which the timing plan was designed.

The City of Detroit may have updated its signals since the information was provided several year ago.

The signal plan named “Good Fixed Plan” was devised to optimize traffic flow for the base traffic scenario. Since traffic in this scenario is predominantly southbound, signals were synchronized along all the major southbound corridors, including Woodward Avenue, Cass Avenue, John R Street, Washington Boulevard, and Randolph Street. The one-way northbound corridor (Brush Street) and the eastbound corridor with the largest volume (Michigan Avenue) were also synchronized, with the crossing intersections timed to work for both directions. These corridors are indicated by heavy lines with arrows in figure 6-l. In all, 102 out of the 132 signals in the network were synchronized. The cycle time and most of the phase splits from the Base Fixed Plan were retained, while the signal offsets and some phase splits were changed. In general, this plan represents an up-to-date fixed timing plan. Note, however, that since the 70 second cycle time for all signals was retained from the Base Fixed Plan, and a global optimization from a program such as TRANSYT-7F was not used, it may not be the best possible fixed timing plan.

6.4.4 Study Methodology

Each combination of a traffic scenario aud a signal strategy is called a case. The simulation was run eight times for each case. Each of the eight runs started with a different random seed, so a different sequence of vehicles was generated. Two runs with different signal strategies but the same scenario and random seed may be compared directly, since each vehicle in one run begins its trip at exactly the same time and origin as its counterpart in the other run. In general however, since the results vary across the random seeds, only the averages across all eight runs should be compared, and the differences checked for statistical significance. In all, there were 240 simulation runs (5 scenarios x 6 signal strategies x 8 random seeds). The DC01 and DC02 strategies differ only in the factors considered in selecting corridors for optimization.

The primary measure of effectiveness was average trip time for all vehicles that began their trips later than 5 minutes but earlier than 25 minutes into the simulation. Leaving out vehicles that began or ended their trips on a lightly loaded network reduced the effects of simulation startup and closedown. Table 6-2 shows the average number of such vehicles in each scenario.

Table 6-2. Number of Vehicles per Scenario

Scenario	Total Number of Vehicles	Vehicles Starting Between 5 and 25 Minutes
Base	9,021	6,142
Light	5,503	3,675
Heavy	11,032	7,362
Alternate	9,195	6,125
Transition	8,956	5,949

For each scenario, the average trip times resulting from each signal strategy were compared to determine whether adaptive signals provided a benefit over fixed signals.

6.5 Presentation and Analysis of Results for Urbansville

Table 6-3 presents the results of the 240 Urbansville simulation runs. The first two columns identify each case by scenario and signal strategy. The first numeric column shows the average vehicle trip time across the eight runs for each case, the second column shows the standard deviation, and the third column shows the difference between the average time for the case and the average time for the Good Fixed Plan case for the same scenario. The fourth column shows the statistical significance of the difference, using the Student's T-test. Significance less than 0.9 does not support the hypothesis that the difference in results is caused by the difference in signal strategies.

Table 6-3. Summary of Simulation Results

Scenario	Signal Strategy	Average Trip Time	Std. Dev.	Trip Time Savings	Stat. Signi-ficance	Savings Pct. of Total	Savings Pct. of Delay
Base	Base Fixed	451	15	-37	1.00	-9%	-15%
Base	Good Fixed	414	13	0		0%	0%
Base	WCI	401	16	14	0.98	3%	5%
Base	DCO1	399	19	15	0.96	4%	6%
Base	DCO2	380	18	34	1.00	8%	13%
Base	Actuated	406	31	8	0.49	2%	3%
Light	Base Fixed	306	4	-23	1.00	-8%	-19%
Light	Good Fixed	283	3	0		0%	0%
Light	WCI	271	7	13	1.00	5%	10%
Light	DCO1	272	6	11	1.00	4%	9%
Light	DCO2	265	5	18	1.00	6%	15%
Light	Actuated	230	3	54	1.00	19%	44%
Heavy	Base Fixed	571	20	-37	1.00	-7%	-10%
Heavy	Good Fixed	534	27	0		0%	0%
Heavy	WCI	498	23	36	1.00	7%	10%
Heavy	DCO1	512	19	22	0.97	4%	6%
Heavy	DCO2	499	20	35	0.98	6%	9%
Heavy	Actuated	551	15	-17	0.91	-3%	-5%
Alternate	Base Fixed	403	20	-1	0.08	0%	0%
Alternate	Good Fixed	402	18	0		0%	0%
Alternate	WCI	358	13	45	1.00	11%	18%
Alternate	DCO1	344	12	58	1.00	15%	23%
Alternate	DCO2	365	24	38	1.00	9%	15%
Alternate	Actuated	303	26	100	1.00	25%	40%

Table 6-3. Summary of Simulation Results (cont.)

Scenario	Signal Strategy	Average Trip Time	Std. Dev.	Trip Time Savings	Stat. Signi- ficance	Savings Pct. of Total	Savings Pct. of Delay
Transition	Base Fixed	408	13	-30	1.00	-8%	-13%
Transition	Good Fixed	378	17	0		0%	0%
Transition	WCI	351	9	27	0.99	7%	12%
Transition	DCO1	350	9	27	1.00	7%	12%
Transition	DC02	345	10	33	1 .00	9%	15%
Transition	Actuated	367	12	10	0.75	3%	5%

The fifth column shows the percent reduction in average trip time (i.e. the savings divided by the average trip time for the Good Fixed Plan case). The sixth column shows the percent reduction in delay (i.e., the savings divided by the average delay time). The average delay time is found by subtracting the weighted average freeflow time from the average trip time for the Good Fixed Plan case. The freeflow time for a path is calculated by dividing the path length by the link speed limit. By definition, the percent savings in delay is greater than the percent savings in trip time. Percent savings in delay is a more meaningful number when analyzing Intelligent Transportation Systems, since delay is the only portion of trip time that can be reduced by ITS. A theoretically perfect ITS system could reduce delay to zero, but could not reduce trip time below freeflow time.

The difference between results for the Base Fixed Plan strategy and the Good Fixed Plan strategy demonstrates the value of building timing plans that provide for progression on the busiest arterials. Such signal retiming is not an ITS activity and should not be counted as a benefit of ITS. The results of adaptive signals were compared to the Good Fixed Plan rather than the Base Fixed Plan so that the benefits of retiming are not included.

Figure 6-2 graphs the average vehicle trip time across the eight runs for each scenario and strategy. Figure 6-3 graphs the difference between the average time for the case and the average time for the Good Fixed Plan case for the same scenario, and figure 6-4 graphs the average time savings expressed as a percent of the average delay time.

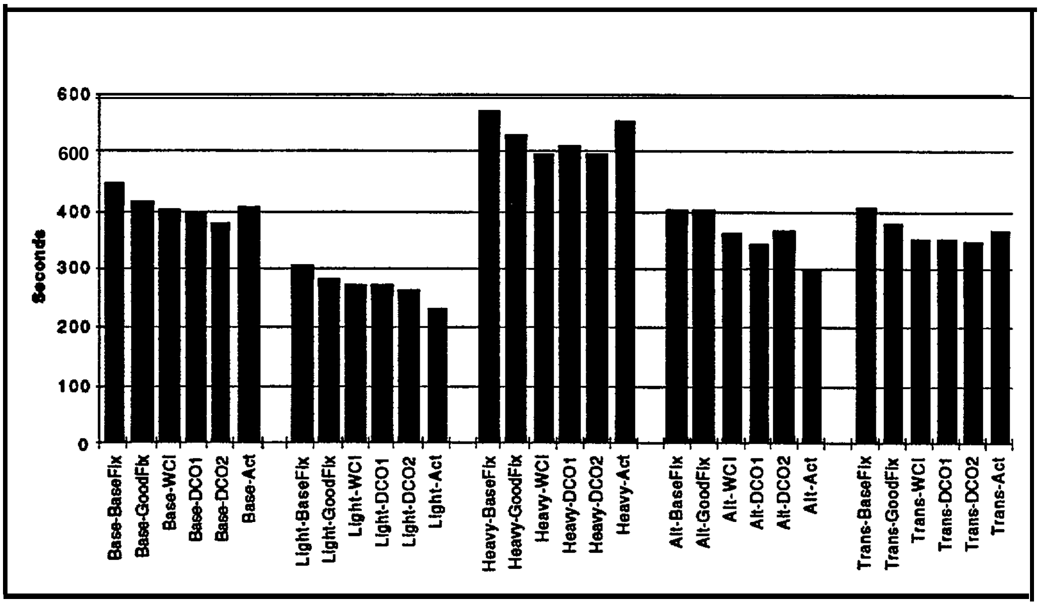

Figure 6-2. Average Trip Times by Scenario and Strategy

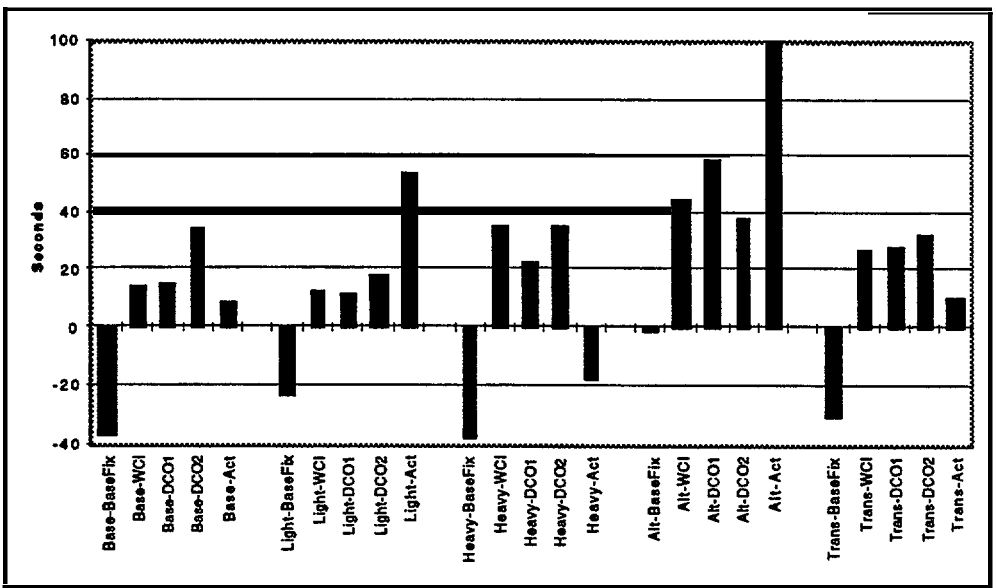

Figure 6-3. Average Time Savings by Scenario and Strategy

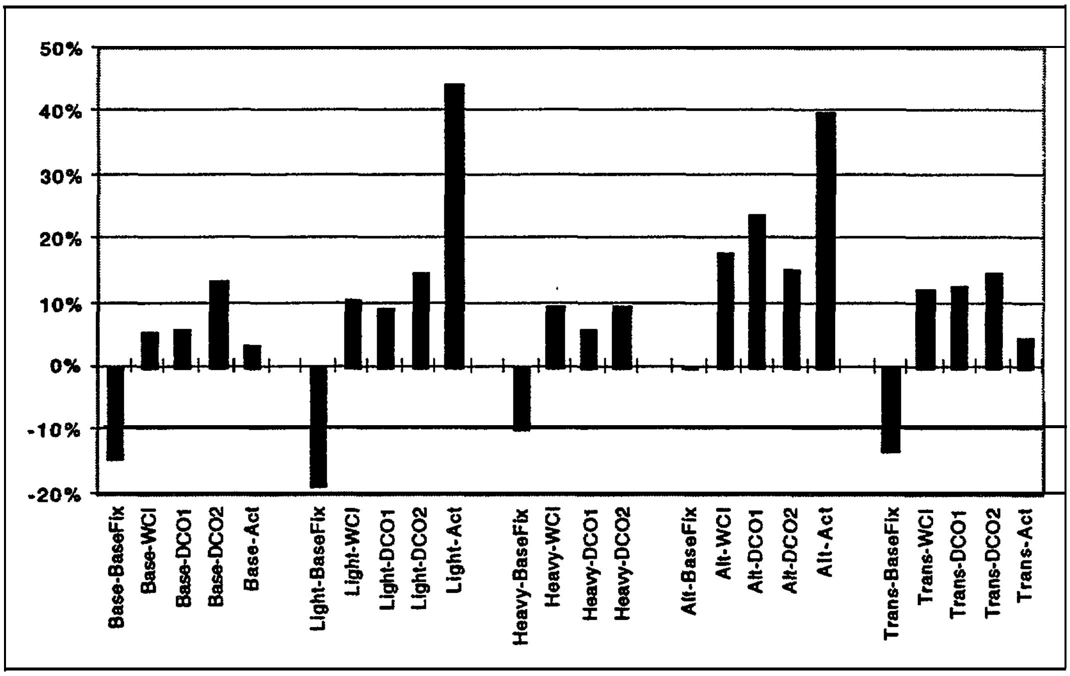

Figure 6-4. Percent of Delay Saved by Scenario and Strategy

The following sections present an analysis of the results for each scenario, highlighting differences between signal strategies and explaining how they came about.

6.51 Base Scenario

As expected, the trip times for the Good Fixed Plan case were significantly better than for the Base Fixed Plan case. Synchronization of the lights along all the major corridors paid off with a 15 percent reduction in delay. Figure 6-S compares the average trip times between one Good Fixed Plan case and the corresponding Base Fixed Plan case, sorted on a path-by-path basis. Vehicles on 24 paths experienced a decrease in average trip time, while vehicles on 22 paths experienced an increase. The paths showing the greatest improvement lie primarily along the synchronized corridors. The paths showing the greatest loss lie along the same corridors but in the direction opposed to the synchronization. Since the southbound traffic had the greater volume, more southbound drivers saved than northbound drivers lost. In addition, the average savings on winning paths exceeded average losses on losing paths. The net total savings was 82 hours.

The average trip times for the three out of the four cases with adaptive signal plans were better than those for the Good Fixed Plan, but not significantly so. Only the DC02 strategy resulted in time savings greater than the standard deviation or greater than ten percent of the delay. Some improvement was possible because half the base traffic did not travel on synchronized corridors and because the Good Fixed Plan was not derived as the best possible fixed plan.

With the exception of the DCO2 strategy, the results support the hypothesis that adaptive signals cannot significantly improve system performance when traffic follows predicted patterns.

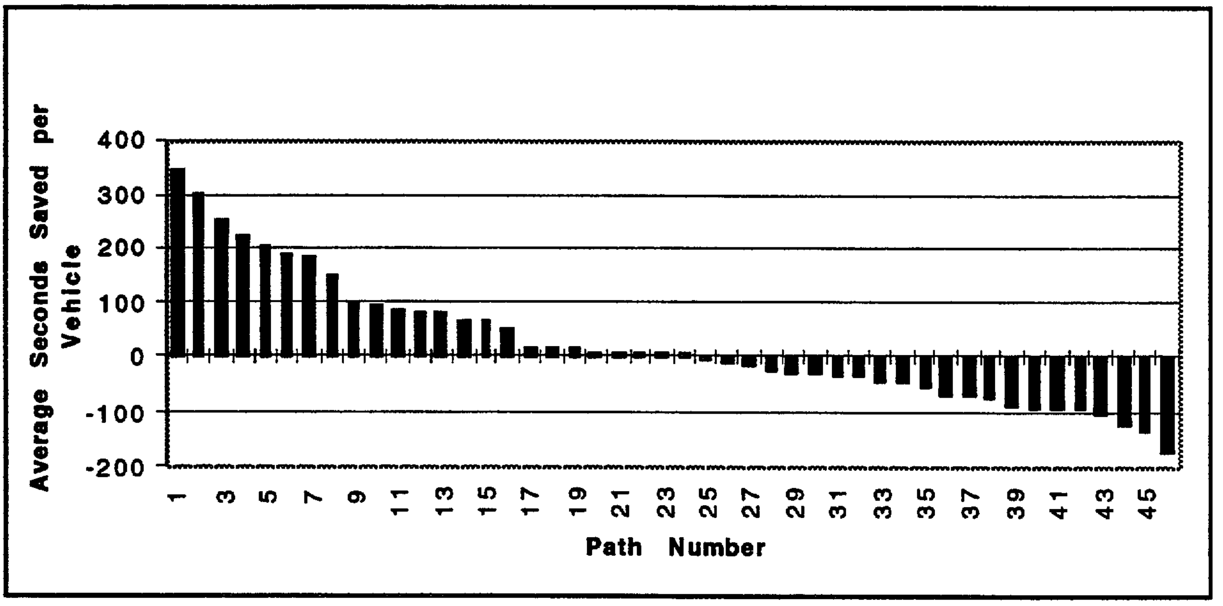

Figure 6-5. Difference in Average Trip Time Between the Good Fixed Timing Plan and the Base Fixed Timing Plan

6.5.2 Light Traffic Scenario

The reduction of traffic levels to 60 percent of the base volumes did not have a significant effect on the relative outcomes of the signal strategies, except for the Actuated signal strategy. The Good Fixed Plan provided a significant benefit over the Base Fixed Plan as expected, and the WCI and the two DCO strategies provided a benefit over the Good Fixed Plan, but these improvements were not significant. The percent time savings did not exceed ten percent for any of these adaptive signal strategies.

Actuated signals, however, provided a significant benefit over the Good Fixed Plan. This result conforms to intuition. Signal actuation works best when a green light is given to approaches with traffic and the red light is given to approaches with no traffic. When traffic is light, this situation happens frequently. The delay due to signals is minimized for this case since most vehicles are given the green light as they approach intersections. The resulting savings is 44 percent of average delay time. To some degree, the concept of using actuated signals for light traffic is similar to the concept employed by some cities of turning off the fixed cycles at night and letting the signals blink red and yellow.

6.5.3 Heavy Traffic Scenario

The increase of traffic by 20 percent on all links creates greater congestion throughout the network and increases the V/C ratio at some intersections to exceed 0.9. The average travel time for all strategies increased significantly over the corresponding cases for the Base case. As for the Base case, the Good Fixed Plan provided a significant benefit over the Base Fixed Plan. The WCI and two DC0 signal strategies were able to make a significant improvement over the fixed timing plan strategies because they increased cycle lengths selectively to move the greater volumes more efficiently. Both the WCI strategy and the DC0 strategies started with cycle lengths of 30 seconds for most signals as the network began to load, and quickly increased them to the maximum cycle length of 180 seconds as the network became loaded.

The Actuated signal strategy, however, performed worse than the Good Fixed Plan strategy. As noted in the previous section, actuation works best when the red light can be given to approaches with little or no traffic. In the Heavy Traffic scenario, this situation was seldom present. Moreover, the actuated signals quickly fell out of synchronization, so the benefit of the corridor progression maintained by the Fixed Plan was lost.

6.5.4 Alternate Scenario

This scenario sends a lower proportion of vehicles along corridors that are synchronized by the Good Fixed Plan The average trip times cannot be compared directly to those for the Base scenario because more vehicles travel in the east-west direction. Since Urbansville CBD is so much narrower in the east-west direction than the north-south direction, the average trip times are shorter. Average trip times can only be compared among signal strategies for this scenario.

In this scenario, the Good Fixed Plan does not result in any improvement at all over the Base Fixed plan since fewer vehicles are traveling the synchronized corridors. However, the WCI and two DC0 strategies result in significant improvement because they are able to adapt to the different traffic volumes. The WCI strategy is successful because the phase splits can be changed to give more time to eastbound and westbound traffic and the cycle lengths can be increased to increase throughput. As the simulation progressed, average cycle lengths increased toward the maximum allowed 180 seconds. The DC0 strategies are successful because they can synchronize signals along corridors with the most traffic rather than the preset corridors.

Table 6-4 shows the sequence of corridors selected for optimization for a typical run of the DC01 case. It shows how the selected corridors change during the course of the simulation as queues develop and dissipate. A corridor that is synchronized during one ten-minute period may not be selected for the next period because two or more of its signals have been already optimized as parts of crossing or opposing corridors. That does not imply that the corridor becomes completely unsynchronized, however. Portions of the corridor will continue to operate in synchronized mode; only two or three of the signals will be out of synchronization.

Table 6-4. Times at Which Corridors Were Chosen for Optimization

Corridor (Street) Name	Simulation time in seconds					
	600	1200	1800	2400	3000	3600
WOODWARD S	X	X	X			X
WOODWARD N					X	
MICHIGAN E		X			X	X
MICHIGAN W				X		
GRAND RIVER E	X		X	X		X
FISHER E	X		X			X
FISHER W	X		X			X
CASS S		X			X	
CASS N						
JOHN R S						
BRUSH N						
RANDOLPH N	X					
RANDOLPH S		X	X	X	X	
WARREN E			X			X
WARREN W	X					
WASHINGTON S	X	X	X	X	X	

Figure 6-6 compares the average trip times sorted on a path-by-path basis between a DC01 case and the corresponding Good Fixed Plan case. Twenty-five paths experienced a net savings in travel time. The total time savings along these paths was 186.7 hours. Eighty-six percent of the time savings occurred on 10 of the paths; these paths lay primarily along northbound corridors. Twenty-one paths experienced a net loss in travel time. The total time loss was 40.8 hours. These paths lay **entirely** or primarily along corridors that enjoyed permanent synchronization in the Good Fixed Plan case, but lost that synchronization at times to other competing corridors in the DC0 cases. The total savings minus the total losses resulted in a net savings of 145.9 hours.

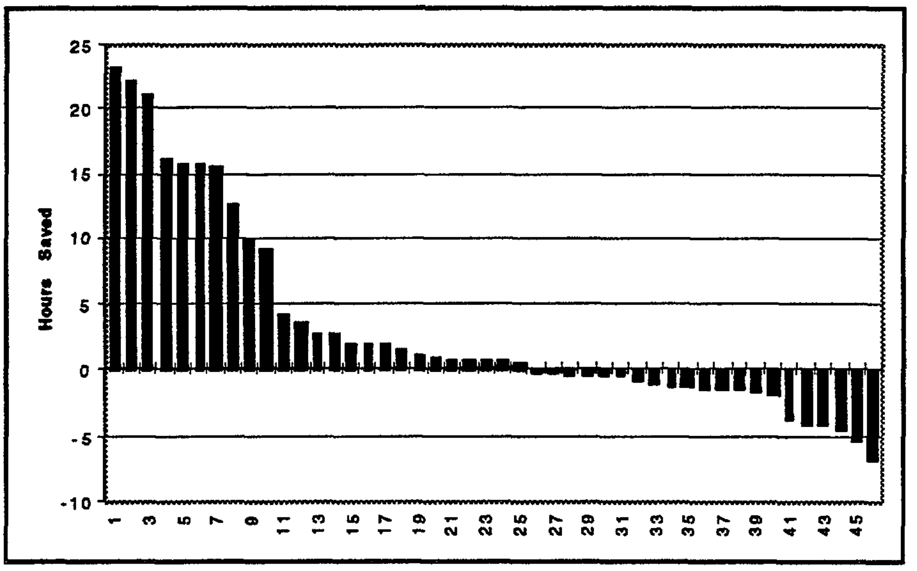

Figure 6-6. Average Time Savings by Path for DCO Compared to Good Fixed Plan

Figure 6-7 illustrates time savings based on a comparison of trip times for individual vehicles. The travel time for each vehicle under one DCO1 strategy run was subtracted from the travel time for the same vehicle under corresponding Good Fixed Plan run, and the resulting values of time savings were sorted and grouped into ten deciles. The bars in figure 6-7 show the total time saved by vehicles in each decile. For example, the top 10% saved a total of 112 hours and the bottom 10% lost a total of 48 hours. The line with small circles shows the average number of seconds saved by vehicles in each decile. For example, vehicles in the second 10% gained an average of 150 seconds and vehicles in the ninth decile lost an average of 61 seconds. In all, the net total savings was 110 hours and the net average savings per vehicle was 43 seconds.

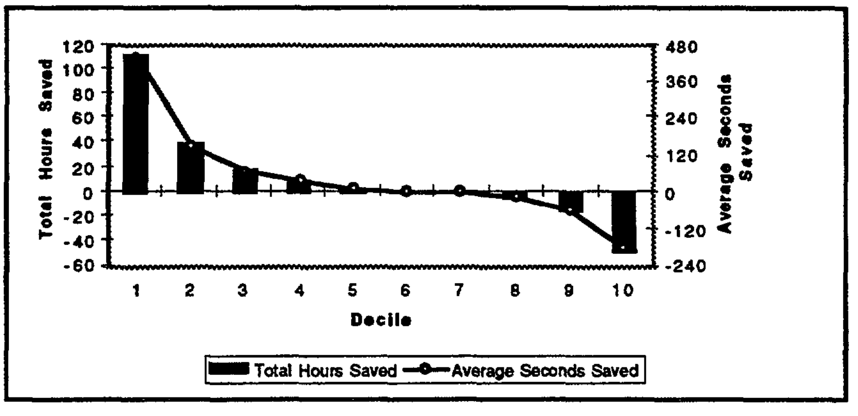

Figure 6-7. Total and Average Savings by Decile

Actuated signals achieve an even more significant reduction in average travel time since green time is not given to approaches that do not need it. The time savings achieved by Actuated signals for this case was the greatest in the study. Part of the savings can be attributed to the fact that Actuated signals began responding to the changed traffic flow immediately, while the WCI strategy required six minutes and the DC0 strategies required ten minutes of operation collecting data before responding with altered timing plans.

6.5.5 Transition Scenario

As expected, the results from the Transition scenario lie between the results for the Base scenario and the Alternate scenario. The good fixed timing plan works well for the first part of the simulation, but grows increasingly out of touch with the traffic as it changes direction. The adaptive signal plans change along with the change in traffic direction. Figure 6-8 shows the average trip time for each group of vehicles that started trips within the same two-minute interval for a typical Fixed Signal run and its counterpart DC01 run. For the first part of the simulation, the Good Fixed Plan strategy and the DC0 strategy have the same timing plans, so average trip times are the same. As the simulation progresses and the prevailing traffic direction changes, however, the DC01 strategy is able to keep average trip times from rising as fast as they do under the Good Fixed Plan strategy. The difference amounts to approximately one minute per trip.

An objection to adaptive signals has been raised, saying, "Of course a given fixed signal timing plan doesn't work well when traffic changes to another arrival pattern. When that happens, simply switch to another predetermined fixed signal timing plan." The Transition scenario demonstrates the value of adaptive signals when traffic is changing constantly, and thus no fixed timing plan is appropriate. Predetermined fixed timing plans also are useless when an unplanned event such as an incident or bad weather changes traffic patterns significantly, or when traffic surveillance systems are not adequate to detect changes in traffic patterns.

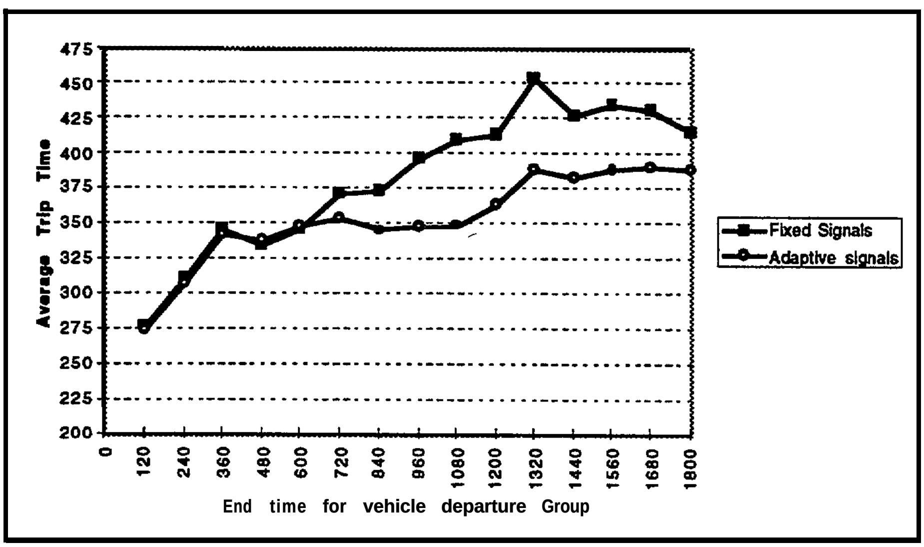

Figure 6-8. Average Trip Time as a Function of Departure Time

6.6 Additional Urbansville Scenarios

Following the study of Urbansville CBD documented in sections 6.4 and 6.5, Mitretek extended the study by creating additional scenarios with intermediate traffic volumes and various intermediate amounts of deviation from the expected direction of traffic flow. This section describes the additional scenarios and the simulation results.

6.6.1 Description of Traffic Scenarios

Mitretek defined 20 scenarios as the product of four levels of traffic volume and five levels of traffic conformity to corridors with pre-defined synchronization. Four of the scenarios from the previous study are included among them.

The Base scenario is the same as described in section 6.4.2, representing the morning rush hour period. The predominant direction of traffic was southbound.

Four traffic volume levels were modeled by multiplying the Base scenario traffic volumes on each path by (a) 60%, (b) lOO%, (c) 110% and (d) 120%. Volumes on each link were affected proportionately.

The five levels of traffic conformity to pm-defined corridor synchronization were defined as follows. In the Base scenario, 47% of the traffic followed corridors with predefined synchronization. Three alternate levels represented increasing amounts of departure from the expected traffic directionality, with 41%, 35%, and 29% of the traffic following pre-defined corridors. In these scenarios, traffic volumes for predominantly northbound, eastbound, and westbound paths were increased and volumes for predominantly southbound paths were decreased by the same amount to keep the total traffic volume constant. The fifth level of directionality sent 53% of the traffic on pre-defmed corridors - a proportion even greater than the Base scenario.

Four signal strategies were compared for these scenarios: the Good Fixed plan, Isolated signal optimization (WCI), Dynamic Corridor Optimization (DCO), and Actuated signals. The DC0 strategy corresponds to the DC02 strategy described in section 6.3, so stop times and travel times are not required. The unoptimized (Base) fixed plan modeled in sections 6.4 and 6.5 was not modeled because the previous work amply demonstrated the benefit of an optimized fixed over an unoptimized fixed plan.

Each combination of a traffic scenario and a signal strategy was called a case. The simulation was run eight times for each case. Each of the eight runs started with a different random seed, so a different sequence of vehicles was generated. In all, there were 640 simulation runs (20 scenarios x 4 signal strategies x 8 random seeds).

6.6.2 Presentation of Results

Table 6-5 presents for each scenario the average vehicle trip time for fixed signals, the percent reduction in average trip time achieved by each adaptive signal strategy, and the percent reduction in average delay. All savings greater than 3% were statistically significant at or above the 90% level, The shaded boxes contain results for cases included in section 6.5.

Table 6-5. Results of Extended Simulation Runs

% Traffic on Corridors Synchronized by Fixed Plan	Traffic Volume as Percent of Base	Average Trip Time Fixed Plan (seconds)	Trip Time Savings (Reduction from Average Trip Time for Fixed Plan)			Delay Savings (Reduction in Average Trip Time - Freeflow Time)		
			WCI	DCO	Act	WCI	DCO	Act
53%	60%	288	1%	3%	18%	1%	7%	40%
53%	Base	449	0%	-1%	-9%	0%	-2%	-14%
53%	110%	511	3%	1%	-8%	5%	2%	-12%
53%	120%	565	4%	0%	-6%	6%	-1%	-8%
47%	60%	283	5%	4%	19%	10%	9%	44%
47%	Base	414	3%	4%	2%	5%	6%	3%
47%	110%	462	2%	3%	-10%	3%	4%	-15%
47%	120%	534	7%	4%	-3%	10%	6%	-5%
41%	60%	285	7%	7%	21%	16%	16%	47%
41%	Base	397	6%	8%	6%	10%	14%	10%
41%	110%	446	5%	2%	7%	8%	3%	11%
41%	120%	491	4%	4%	11%	6%	5%	16%
35%	60%	283	12%	8%	24%	27%	20%	56%
35%	Base	403	12%	15%	13%	19%	24%	22%
35%	110%	439	10%	11%	16%	16%	17%	25%
35%	120%	484	8%	7%	15%	12%	11%	22%
29%	60%	285	11%	10%	24%	23%	21%	51%
29%	Base	402	11%	15%	25%	18%	23%	40%
29%	110%	460	13%	14%	21%	19%	21%	31%
29%	120%	495	11%	13%	20%	15%	18%	29%

Figures 6-9 through 6-11 present contour plots of the percentage of trip time savings over the fixed plan for the three adaptive strategies. Figure 6-12 shows the maximum benefit over all three adaptive strategies. The benefits shown in figure 6-12 could be obtained by a signal control system that could switch between actuated and synchronized operation as conditions warranted, or that could operate in actuated mode while retaining corridor synchronization.

The following sections present an analysis of the results for each signal strategy, highlighting the scenarios in which they performed well or poorly. Points made in section 6.5 are not repeated.

6.6.3 Isolated Signal Optimization

As shown in figure 6-9, isolated signal optimization provided a benefit over fixed signal operation in all scenarios. The ability to adjust phase splits based on immediate past experience always helped. The size of the benefit increased as the deviation from expected direction of traffic flow increased. In the scenarios with a significant change in traffic directionality, this scheme achieved over a 15% reduction in delay. There was also a benefit when traffic followed expected corridors but was heavier than expected. In fact, WCI was the best adaptive signal strategy in those cases.

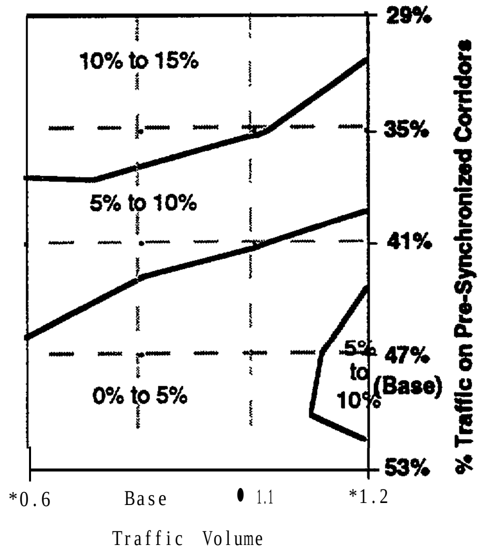

Figure 6-9 Percent Reduction in Average **Trip Time**
Isolated Signal Optimization

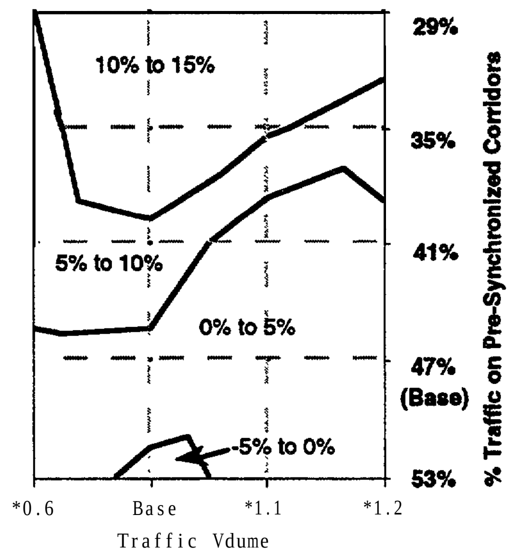

Figure 6-10. Percent Reduction in Average Trip Time
Dynamic Corridor Optimization

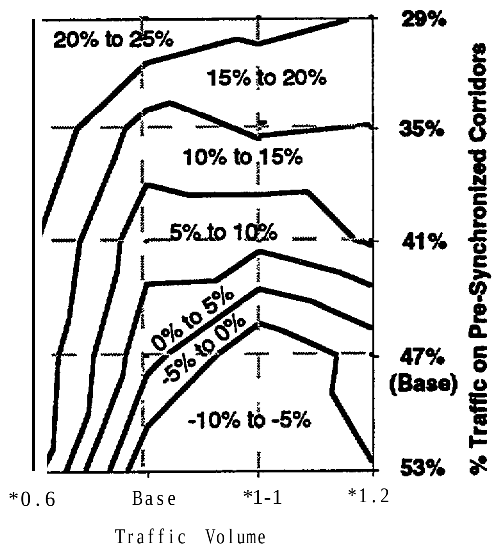

Figure 6-11. Percent Reduction in Average Trip Time
Actuated Signals

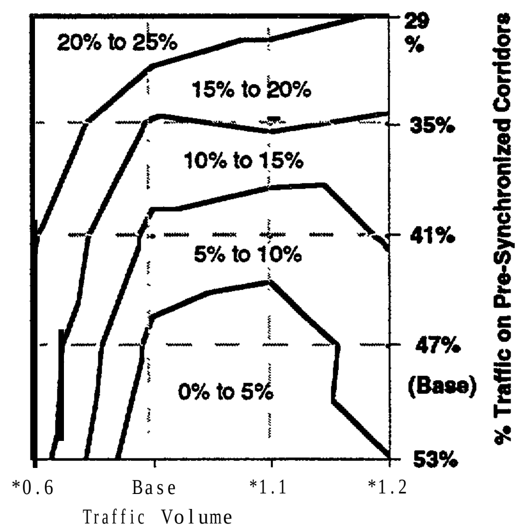

Figure 6-12. Percent Reduction in Average Trip Time
Rest Adaptive Strategy

6.6.4 Corridor Optimization

As shown in figure 6-10, corridor optimization provided a benefit over fixed signal operation in all but one scenario. In the scenarios where traffic directionality matched expectations, corridor optimization did not provide greater benefits than Webster-Cobbe isolated signal optimization. This is because the WCI strategy started off with the Fixed Plan as its initial state, so the corridors most needing synchronization were already synchronized. In the scenarios with the greatest deviation, however, corridor optimization provided better results than isolated signal optimization. This is because northbound and westbound corridors benefited from synchronization more than the default corridors synchronized by the Fixed Plan and perpetuated to some extent by the WCI strategy.

6.6.5 Actuated Signals

In all light traffic scenarios, actuated signals provided a significant benefit over the Fixed Plan. Actuated signals were able to exploit gaps in traffic, giving extended green time to approaches with traffic and giving the red time to approaches with no traffic. The amount of traffic deviation from expected directions was not a significant factor in light traffic.

In scenarios where traffic directionality differed from expectations, actuated signals also resulted in significant time savings. Reacting to actual traffic rather than sticking to an obsolete fixed plan provided the greatest benefits in the study. However, when traffic directionality conformed to expectations and the demand was heavy, actuated signals performed worse than fixed signals. In those cases, actuated signals did not have an advantage because there were no gaps in traffic to be exploited and the benefit of corridor synchronization was lost. In those situations actuated signals should revert to traditional phased control or to actuation within a cycle determined by corridor synchronization.

The actuated signal control modeled by THOREAU is more sophisticated than most actuated signals currently in operation. Queue lengths are estimated by keeping a count of the vehicles entering the intersection with a detector at the stop bar and subtracting it from the number of vehicles counted by a detector 100 feet upstream. In practice, the queue length at an intersection could be also be obtained by a series of presence-detecting loops or by using a video camera with the intelligence to count vehicles.

6.6.6 Hybrid Adaptive Signals

Figure 6-12 shows the benefits that might be obtained with an adaptive signal system that uses isolated or synchronized signal optimization when the observed traffic is close to the expected volume and directionality, and uses actuation when the observed traffic volume or directionality is significantly different from the expected values. Alternatively, the system could use actuated signals that operate within a common cycle length and offsets established to maintain corridor progression. In either implementation, the adaptive signals would always provide a positive benefit over fixed signals. Mitretek is currently adding to THOREAU the ability to model hierarchical actuated signals that adapt to real-time traffic flow while maintaining synchronization. Those signals should combine the advantages of both DC0 and Actuated strategies.

6.7 Description of the GRID Scenario

prior to the Urbansville network study, Mitretek constructed a sample network called GRID. The network was kept simple to focus on the issue of adaptive signals, yet have realistic traffic levels and turning movements. The study is included in this paper because it gives some additional insights into adaptive signal operation and it provides the opportunity to compare results from INTEGRATION and THOREAU. The results for INTEGRATION were originally reported by Harding (1995) and the combined results were originally reported by Glassco (1995b).

6.7.1 Description of the GRID Network

Figure 6-13 shows the GRID network. The network consists of six major two-way streets (three east-west and three north-south) and eight minor one-way streets feeding onto the major streets. The major streets have two lanes in each direction and the minor streets have one lane. The length of each link is 250 meters. The saturation rate of the links is 1500 vehicles per lane per hour.

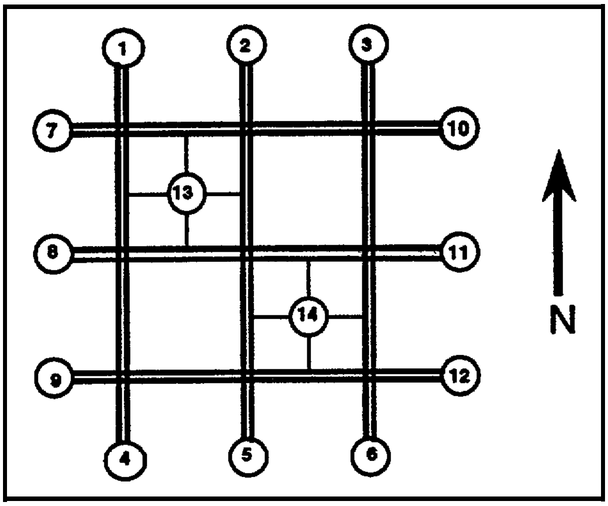

Figure 6-13. The GRID Network

The twelve nodes around the outside are origins and destinations for traffic on the major streets. The two internal nodes (13 and 14) are origins of background traffic to the outside no&s. There are nine nodes at the intersections between major streets and eight nodes at the intersections between a major street and a minor street. A traffic signal is modeled at each of the nine intersections between major streets. Stop signs are modeled where minor streets empty onto major streets. Protected turns and pocket turn lanes at intersections arc not modeled.

Each major street is defined as a corridor with no turns. The minor streets arc not part of any corridors. Thus there are 12 corridors (three in each direction). Every traffic signal belongs to four corridors (one in each direction).

6.7.2 Base Case Traffic Demand Scenario

Table 6-6 defines the base case demand on the network. There is one major stream of traffic along each of the 12 corridors. The distance traveled on each path is one kilometer, and the fieeflow time is 64 seconds at a speed of 56 kph (35 mph). There are also 8 minor streams of traffic originating at the internal nodes. The latter streams am called background traffic. Although the hourly flow volume for the background traffic is small, it introduces delay at the intersections because of vehicles making left and right turns.

Table 6-6. Base Case Demand Scenario

	Average Interarrival Rate (sec.)	Average Vehicles per hour	% of Total Traffic
Southbound	1.31	2 748	30%
Northbound	2.44	1474	16%
Eastbound	1.51	2380	26%
Westbound	4.13	871	9%
Background	2.04	1764	19%
Grand total		9,237	100%

The predominant directions of traffic demand along the corridors arc east and south, and the center corridor carries the greatest traffic in each case. The background traffic also flows predominantly in the east and south directions. Given the saturation rate of the links, the average intersection V/C ratio at the major intersections is 0.65.

Both THOREAU and INTEGRATION models ran for two hours of simulated time. During the first hour, traffic was generated randomly with the average hourly demand rates shown in table 6-6. Over 9,200 vehicles were created during the first hour. During the second hour, no new traffic was generated, but traffic already in the network was permitted to finish.

6.7.3 Base Case Fixed Signal Plan

Mitretek developed a set of fixed signal timing plans, given the network and demand patterns described above, using the TRANSIT-7F signal optimization program. This program computes optimal cycle lengths, phase splits, and offsets given traffic volumes for each approach to an intersection. Since the highest demand occurs in the center eastbound and southbound corridors, the signal in the center is the busiest. TRANSYT-7F determined that 60 seconds is the optimum cycle length for that signal. To enable progression in the eastbound and southbound directions, the cycle lengths for the other signals in those corridors were set to 60 seconds as well. The cycle lengths for the four comer intersections were set to optimum values given the volume of traffic at each intersection. TRANSYT-7F also computed the phase splits for each signal, given the traffic volume in each direction. The offsets for the signals were set so that progression at 56 kph (35 mph) is achieved for the center eastbound and southbound corridors.

6.7.4 Alternate Demand Scenarios

Four alternate scenarios were developed to test the hypothesis that adaptive signals give a benefit when traffic behaves differently than expected.

1. The first of these, entitled “Switch,” represents a high volume of traffic in a direction different than the ones for which the fixed signal plans are designed. The demand on Eastbound, Westbound, and Southbound corridors is reduced by 30 percent and the

same volume of traffic is added to Northbound corridors. The volume of background traffic and the total volume are unchanged.

2. The second alternate scenario, entitled "Combo," is a combination of the Base case and the Switch case. The traffic arrives at base levels for the first half hour, and then changes to the arrival pattern of the Switch scenario for the second half hour. This scenario represents a case where the traffic patterns change significantly during the simulation.

3. The third alternate scenario, entitled "Rush," represents an increase to the total traffic volume present in the other cases. The traffic volume is kept at base levels for Eastbound, Westbound, and Southbound corridors, while the traffic on Northbound corridors is at "Switch" levels. The volume of background traffic is unchanged.

4. The fourth alternate scenario, entitled "Light," represents a decrease of 33 percent in the volume of traffic for all origin-destination pairs. This could represent the situation where lights are timed for rush hour, but left with those timings during non rush-hour periods.

To reduce the effect of random number generation, each THOREAU case was run with six different starting random number seeds, and each INTEGRATION case with ten different starting random number seeds.

6.8 Presentation and Analysis of Results for the GRID Scenario

This section presents the results of the simulation runs and an analysis of the results. THOREAU results are presented first, followed by INTEGRATION results, followed by a comparison of the two sets of results. In all the following presentations, the fundamental program output reported is the average trip time in seconds for all vehicles. Measures of effectiveness derived from the average trip time are (1) the average amount of time saved per vehicle when comparing the results of a scenario with adaptive signals to the fixed signal base case, and (2) the percent of delay time saved by the adaptive signal control strategy. The latter figure is computed by dividing the average time savings by the average delay for the fixed signal case.

6.8.1 THOREAU Results

Figure 6-14 graphs the average trip time for each scenario and ATMS strategy.

For the Base case, only actuated signals could improve on the fixed signal timing plan. The fixed signals maintained progression for the corridors with the greatest amount of traffic and were not thrown off by random fluctuations about the average flow rates. Isolated signal optimization performed as well as fixed signals, but the corridor optimization routines performed worse.

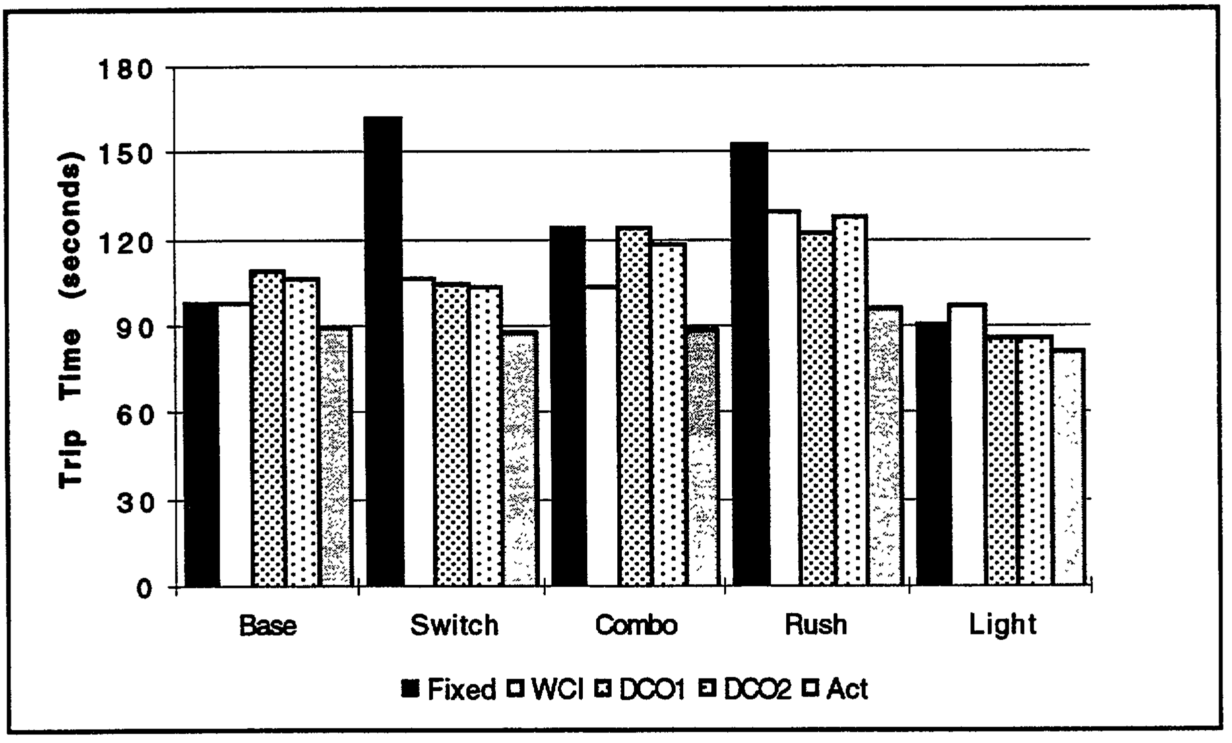

Figure 6-14. Average Trip Time by Scenario and Strategy

For the Switch and Rush cases, all four adaptive signal strategies outperformed the fixed signal timing plans, with a significance level of 1.00. The high volume of traffic in the Northbound direction (against the preset progression) was handled efficiently by the adaptive signals, but very inefficiently by the fixed signals.

For the Combo case, both actuated and Webster-Cobbe isolated signals significantly outperformed fixed signals, but the corridor optimization routines did not. The Combo scenario can be regarded as an average between the Base case and the Switch case, so it is not surprising that the benefits were averaged as well. This result suggests that the benefits of adaptive signals depend on the time interval over which the travel times are measured.

For the Light traffic case, even though the amount of delay for the fixed signal strategy was small, actuated signals and corridor optimization outperformed fixed signals. Although the traffic was uniformly lighter, the heaviest traffic was still in the Southbound and Eastbound directions, so fixed signals did better that isolated signal optimization, which could not keep the progression for these major corridors.

In all cases, the standard deviation is much less than the magnitude of the average trip time. In most cases the average time savings is greater than two standard deviations, suggesting that observed benefits are significant from a statistical standpoint. The pairwise T-Test, which takes into account the variance in each sample set, shows that in almost every case where adaptive signals provide a benefit, the benefit is statistically significant at greater than the 95 percent level.

6.8.1.1 Comparison of Travel Time Saved

Table 6-7 presents the average percent time savings achieved by each adaptive signal control system when compared to the average time for the fixed signals and the time saved as a percent of the delay experienced for the fixed signal case. Figure 6-15 presents the delay information in graphic form. The delay is equal to the average trip time for the fixed signal case minus the freeflow time. The freeflow time is the same for all scenarios, but the delay is different for each scenario.

Table 6-7. Percent Reduction in Trip Time and Delay

	Percent Reduction in Trip Time				
	Base	Switch	Combo	Rush	Light
WCI	0%	34%	16%	15%	-7%
DCO1	-11%	36%	0%	20%	5%
DCO2	-8%	36%	4%	16%	5%
ACT	8%	46%	28%	37%	10%
	Percent Reduction in Delay				
	Base	Switch	Combo	Rush	Light
WCI	0%	57%	33%	27%	-24%
DCO1	-31%	59%	-1%	34%	16%
DCO2	-24%	60%	9%	28%	18%
ACT	24%	75%	58%	64%	33%

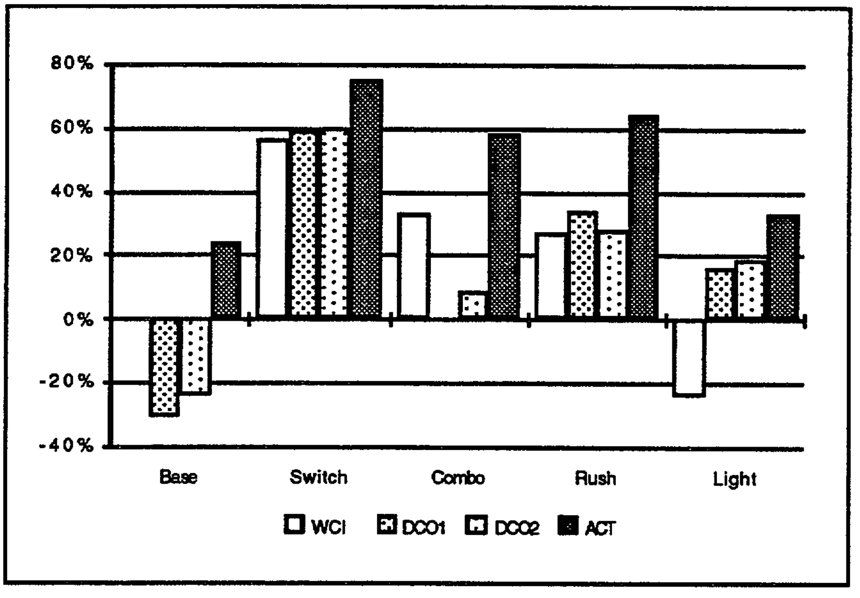

Figure 6-15. Percent Reduction in Delay

The percent of delay reduced because of adaptive signal control strategies is the best metric of the potential benefit of ATMS systems. These systems do not necessarily require the ITS system architecture for implementation, but the ITS system architecture can encourage and support them.

6.8.1.2 Webster-Cobbe Isolated Signal Optimization

THOREAU' s implementation of Webster-Cobbe isolated signal optimization resulted in a savings in travel time for the Rush, Switch, and Combo scenarios. These scenarios had significant traffic against the preset progression and crossing the Eastbound corridors, so the ability of this option to select new cycle lengths and phase splits more than compensated for the loss of progression along the corridors. For these cases where the traffic pattern did not conform to the expected pattern, the time savings ranged from 27 percent to 57 percent of the &lay from freeflow time. The greatest benefit occurred when the traffic was heavy.

The reason the WCI strategy succeeded was that it selected better signal cycle lengths and better phase splits than the fixed plans. Cycle lengths selected during the simulations varied from 30 seconds (the minimum permitted) to 120 seconds (the maximum permitted), with values for a given signal changing every five minutes during the course of the simulation.

WCI performed about as well for the Base case as the fixed signal plans did. The average benefit for the Combo is between the benefit for the Base case and the benefit for the Switch case, as expected.

In the Light traffic case, the WCI strategy performed somewhat worse than the fixed signal strategy. With the smaller number of vehicles, there was no benefit to be gained by losing synchronization to gain shorter cycle times, even on the major corridors.

6.8.1.3 Corridor Optimization

The first result is that there was no significant difference between the two corridor optimization schemes. When the most congested corridors were selected, it did not matter significantly to the overall results whether queue length and trip time were included or not This result suggests that expensive equipment for detecting queue lengths and calculating trip times may not be necessary for realizing the benefits of corridor optimization.

The second result is that both corridor optimization schemes provided a time savings over the fixed signal case in the Switch, Rush, and Light demand cases. The time savings ranged from 16 to 60 percent of the delay from freeflow time. The savings were greatest in the Switch scenario, with the greatest proportion of traffic in an unplanned-for direction.

The benefit achieved by these schemes is roughly the same as the benefit provided WCI strategy for the Rush and Switch cases. There is a greater value to corridor synchronization in the Urbansville scenario where there are much longer corridors.

A closer analysis of the operation of corridor optimization reveals how the scheme works. Table 6-8 is a sample of the sequence of corridors selection for the Combo scenario. At the beginning, the Southbound and Eastbound corridors have the greatest traffic and the greatest congestion, so they are chosen for optimization, with the exception of Northbound corridor 3 at time 600. At time 1800 seconds, the heavy surge of Northbound traffic starts, and creates greater congestion for that direction. When the corridor optimization routine is next invoked at time 2400 seconds, it recognizes that the Northbound corridors are the most congested and synchronizes them. The Northbound corridors continue to command the highest priority at time 3000. At time 3600, however, the congestion on the Eastbound corridors has increased to the point where three Eastbound corridors are selected for optimization.

Table 6-8. Sample Sequence of Corridor Optimization

Time	Corridors Selected for Optimization			
	First	Second	Third	Fourth
600 seconds	S2	N3	S1	
1200 seconds	E2	S3	S2	S1
1800 seconds	S1	E2	S3	S2
2400 seconds	N3	N2	N1	
3000 seconds	N2	N3	N1	
3600 seconds	N2	E2	E3	E1

Figure 6-16 shows the trip time for each vehicle on Northbound corridor 3 for the same example. Looking at figure 6-16, it can be seen that the trip time at the start of the simulation is long (the signals are initially synchronized in the Southbound direction) so the corridor is selected for synchronization at the first opportunity (time 600). Almost immediately the trip time begins to drop to the base level. At time 1800, the traffic increases dramatically on that corridor (the dots on the scatter plot are denser) and the travel time goes up. At time 2400 and 3000 this corridor is selected for synchronization.

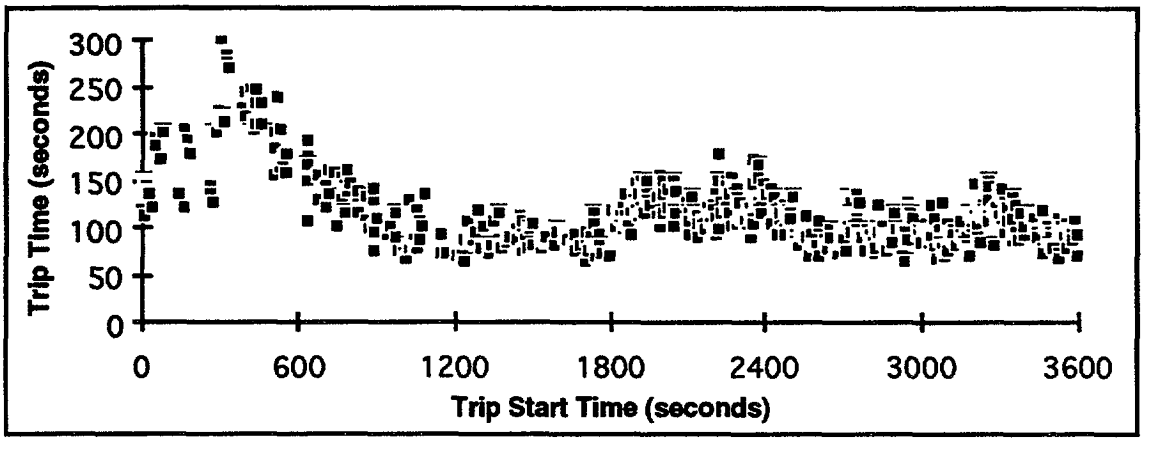

Figure 6-16. Trip Times for Northbound Corridor 3

Figure 6-17 shows what happens to a corridor that competes with the Northbound corridor. It shows this the trip time for each vehicle on Eastbound corridor 2 for the same example. Initially the congestion is not bad, and the corridor is not chosen. After conflicting corridors are chosen at time 600, however, travel time rises dramatically. At time 1,200 and 1,800 the corridor is chosen, and the trip times drop accordingly. Since the Northbound corridors are favored for the second half of the scenario, congestion again increases and the corridor is selected at time 3,600.

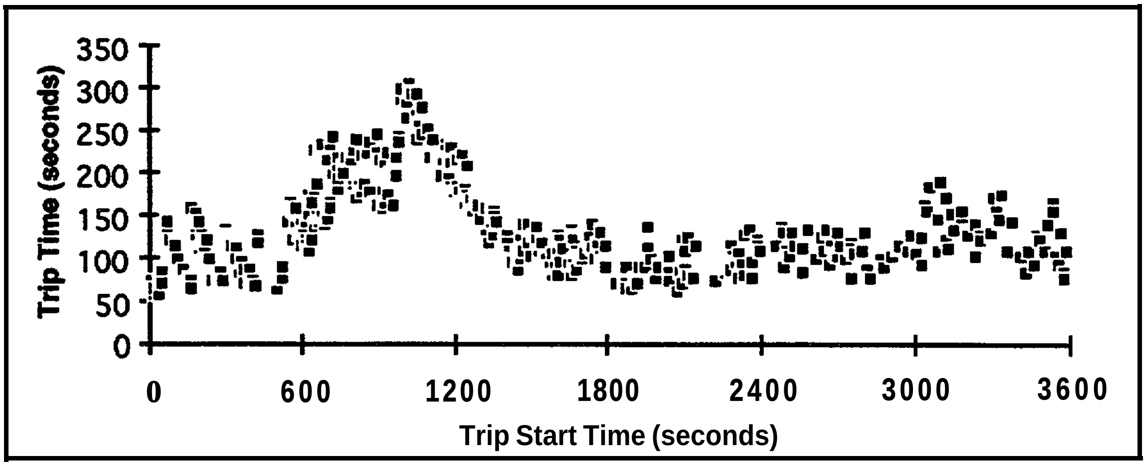

Figure 6-17. Trip Times for Eastbound Corridor 2

The THOREAU test results indicate that a network of sophisticated total actuated signals can perform best of all strategies in all cases. It is not surprising that it outperforms fixed timing and WCI because it is the most sophisticated and responsive system, although it is not synchronized. The system adapts to the traffic present on an up-to-the-second basis, not basing its estimate of traffic volumes on a previous time period.

6.8.1.4 Actuation

It should be pointed out that the actuated signal control modeled by THOREAU is more sophisticated than most actuated signals currently in operation. Not only does it count vehicle actuations with a detector placed upstream from the intersection, but it knows the queue length of stopped vehicles. Earlier versions of THOREAU did not have the latter feature, and the actuated controller performed poorly when there was heavy traffic or a sizable group of vehicles making left turns. The controller would estimate how much time was necessary for the number of vehicles corresponding to the number of recent actuations to clear the intersection, but that time was not sufficient when vehicles had to wait for left turns. The discrepancy between the controller's estimate of vehicles present and the actual number kept increasing. Once a knowledge of queue lengths was added to the model, the actuated controller did very well at setting the best amount of green time for each approach. In practice, the queue length at an intersection could be obtained by a series of presence-detecting loops, by counting the vehicles entering the intersection with a detector at the stop bar and subtracting it from the number of vehicles counted by an upstream detector, or by using a video camera with the intelligence to count vehicles.

6.8.1.5 Comparison of Trip Time by Corridor

Figure 6-18 presents a comparison of average trip time on a corridor-by-corridor basis for the same scenario shown in figures 6-16 and 6-17. It shows that adaptive signal control results in an improvement for most individual corridors as well as for the whole. For some corridors with poor default progressions, (notably Northbound 3 and Westbound 3) the savings are considerable, while a few corridors that benefited from the fixed signal strategy (Eastbound 2 and Eastbound 3) experienced a slight increase in the average trip time. Overall, the average trip time was reduced.

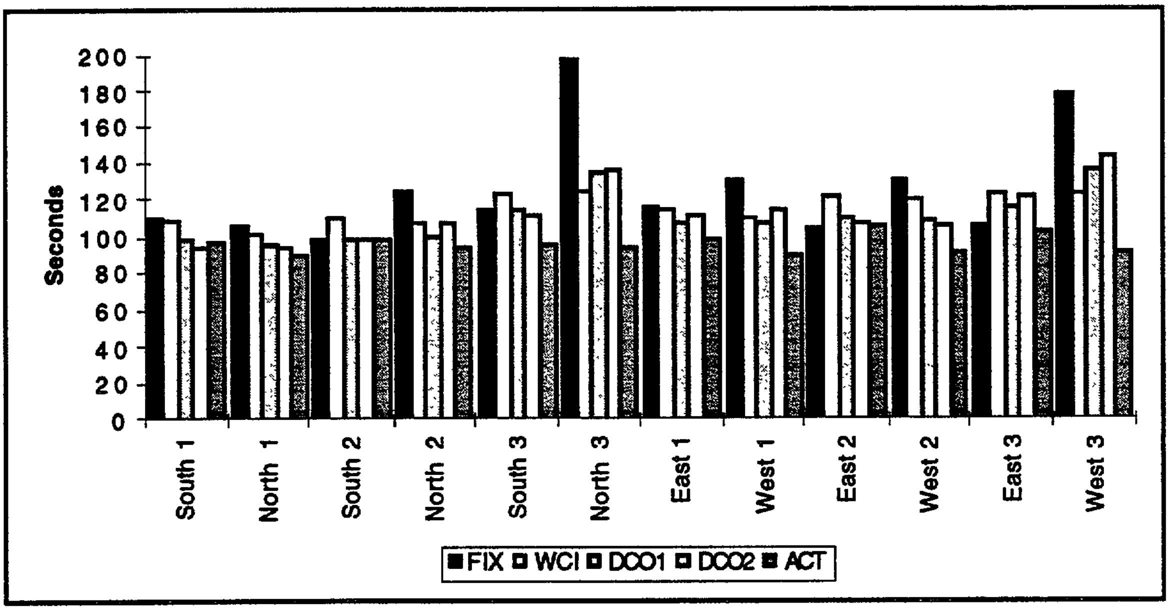

Figure 6-18. Average Trip Time per Corridor

6.8.2 INTEGRATION Results

The results of the INTEGRATION runs are similar to the those of the THOREAU runs, except for the DCO strategy for the Rush scenario. Table 6-9 presents the average percent reduction in trip time and delay for each scenario. The time savings for the Switch scenario far exceed the standard deviation among the simulation results. The results for the Combo and Rush scenarios are not conclusive. Figure 6-19 graphs the average time saved as the difference between the average trip time with the ATMS strategy and the average trip time with fixed signal timing plans.

Table 6-9. INTEGRATION Results

	Base	Switch	Combo	Rush	Light
	Percent Reduction in Trip Time				
	Base	Switch	Combo	Rush	Light
WCI	-17%	38%	3%	11%	3%
DCO	-23%	32%	2%	-4%	8%
	Percent Reduction in Delay				
	Base	Switch	Combo	Rush	Light
WCI	-54%	62%	7%	18%	12%
DCO	-70%	53%	5%	-7%	30%

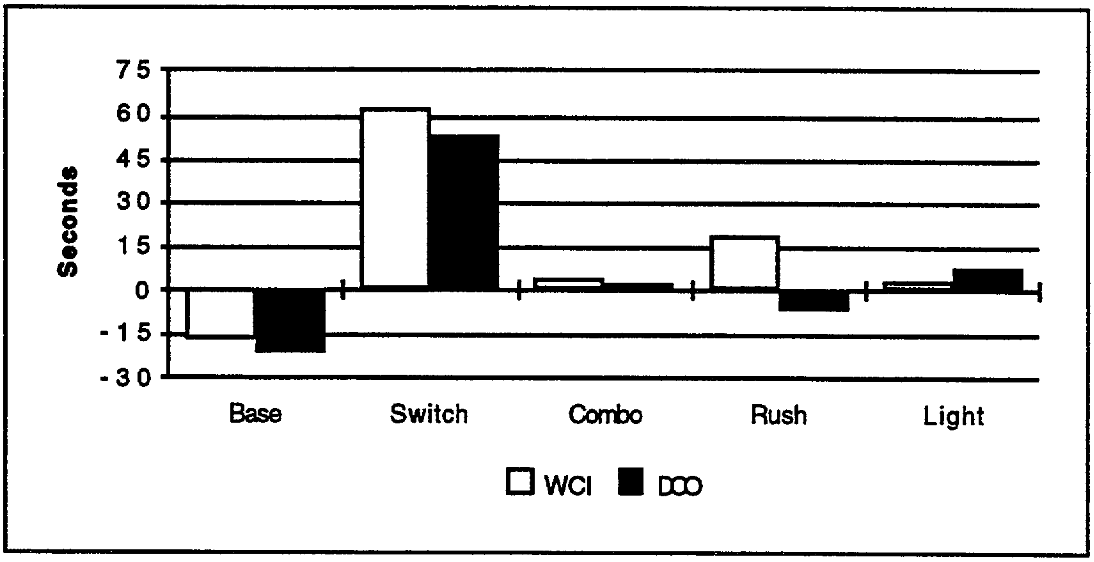

Figure 6-19. Average Time Savings

In general, the results for INTEGRATION confirm the results presented for THOREAU. In particular, WCI and DCO strategies cannot improve on the fixed timing plans for the Base case, but can help significantly in the Switch scenario. The results for the Combo scenario lie between the results for the Base and Switch scenario as expected. WCI provides a benefit for the Rush scenario, but DCO does not.

6.8.3 Comparison of THOREAU and INTEGRATION Results

Figure 6-20 shows the results of the INTEGRATION and THOREAU simulations together for the ATMS strategies they have in common. The second corridor optimization strategy and signal actuation were not modeled with INTEGRATION. The two sets of results clearly track each other well, except for the Rush scenario with the WCI and DCO strategies. The other results for the other cases are very close. The correlation coefficient between the two sets of numbers is 0.86.

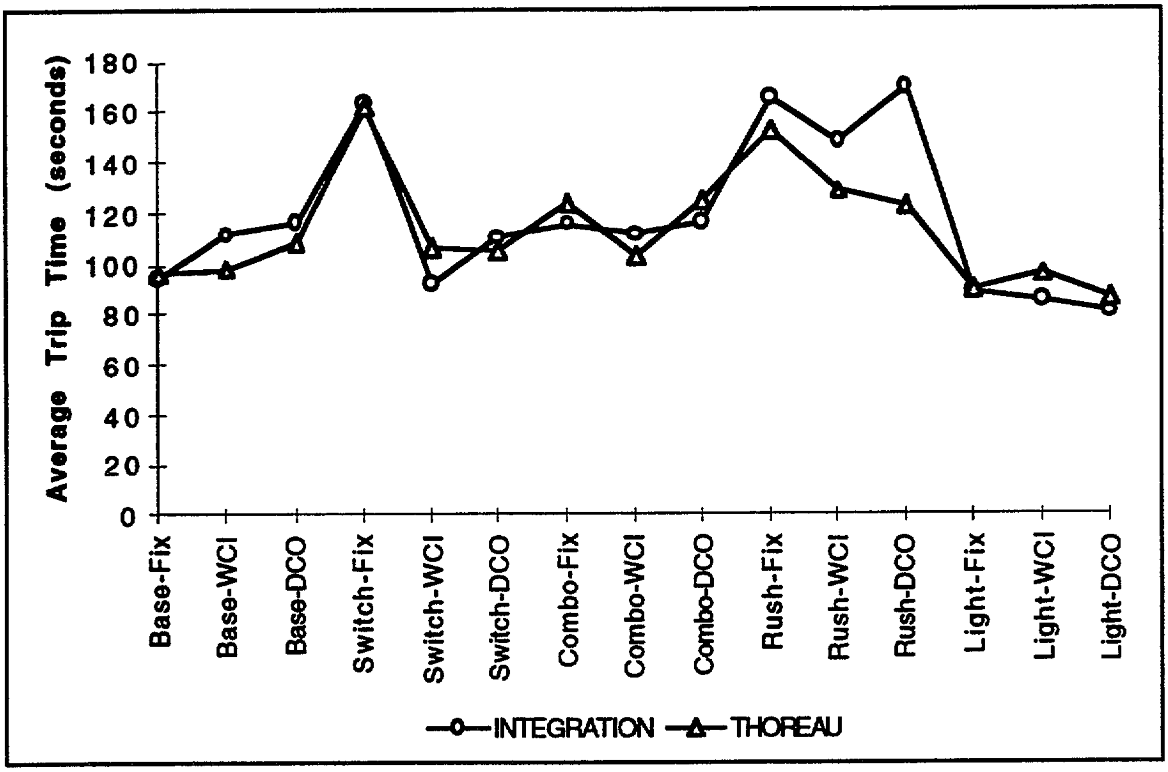

Figure 6-20. Comparison of THOREAU and INTEGRATION Average Trip Times

THOREAU and INTEGRATION are very different in approach, level of detail, and modeling procedures. Nevertheless, the two models produce very similar results for the GRID network. They indicate the same relative merits of WCI and corridor optimization in comparable scenarios. The results reported here are thus more strongly supported than would be the case if they were produced by one model only. Further, it is in effect a validation of the two models against each other, providing evidence that the two models produce reasonable and consistent results.

6.9 Conclusions

This section presents observations and conclusions concerning the potential benefit of ATMS from the results of the THOREAU and INTEGRATION studies.

6.9.1 Corridor Synchronization

In all but one scenario (the one with base volume and even more traffic on pre-established corridors than anticipated), corridor optimization provided a benefit over fixed signal operation. In the scenarios where the base case directionality was maintained, corridor optimization did not provide greater benefits than Webster-Cobbe isolated signal optimization.

This is because (a) traffic directionality matched expectations and (b) the WCI strategy started off with the Good Fixed Plan as its initial state, so (c) the corridors typically benefiting from synchronization were already synchronized. In scenarios where the traffic directionality differed from expectations, however, corridor optimization provided better results than isolated signal optimization. This is because different corridors benefited from synchronization more than the default corridors synchronized by the Good Fixed Plan and perpetuated to some extent by the WCI strategy.

6.9.2 Actuated Signals

In all scenarios with lighter than expected demand or a smaller than expected proportion of traffic on pm-established corridors, actuated signals provided a significant benefit over other fixed timing plans. Actuated signals did not work as well in heavy traffic and expected traffic levels on pre-established corridors because corridor synchronization was lost and there were no gaps in traffic to exploited. These results confirm the value of responding to the immediate situation rather than previous experience if the immediate situation is different than expectations.

6.9.3 The Value of Adaptive Signals

The results of this study support the hypothesis that adaptive signals do not provide a significant benefit over a good fixed timing plan if traffic conforms to the volume and directionality for which the timing plan was designed. Adaptive signals can provide significant benefits when traffic deviates from the expected pattern, either in total volume or directionality. The more traffic departs from the base case, the more benefit is obtained from adaptive signals. The term “significant” can be used in terms of statistical significance, meaning that it is valid to infer that the difference in signal strategies causes the observed differences in average trip times. It can also be interpreted to mean that savings of over 10 percent in average trip time or average trip delay time can be achieved over the portion of the network modeled.

The adaptive signals as implemented are sensitive to changes in demand, so they are more responsive and more effective when significant and sustained demand shifts occur. However, they are more unstable, and therefore less effective, when only random variation is detected and no significant demand shift is present.

In most cases, actuated signals provided a greater benefit than any other method of signal control. This result confirms the value of responding to the immediate situation rather than previous experience. The actuated controllers modeled are more sophisticated than those currently in use, however, because they know intersection queue lengths.

In general, the more information is known about the current state of traffic, the more responsive and effective the traffic control system may be. When traffic does not conform to predicted patterns, the percent reduction in average trip time achieved by adaptive signals ranges from 5 to 25 percent. Greater deviations from expectations provide the opportunity for greater benefits. These results indicate a clear value for ATMS as a part of the ITS system architecture.

Figure 6-21 is one way of illutstrating the best adaptive signal strategy for each scenario. The origin is the base scenario, with traffic at expected levels and directions. The horizontal and vertical dimensions of traffic volume and conformity to pre-synchronized corridors are the same as those found in figures 6-9 through 6-12. The study results can be summarized as follows.

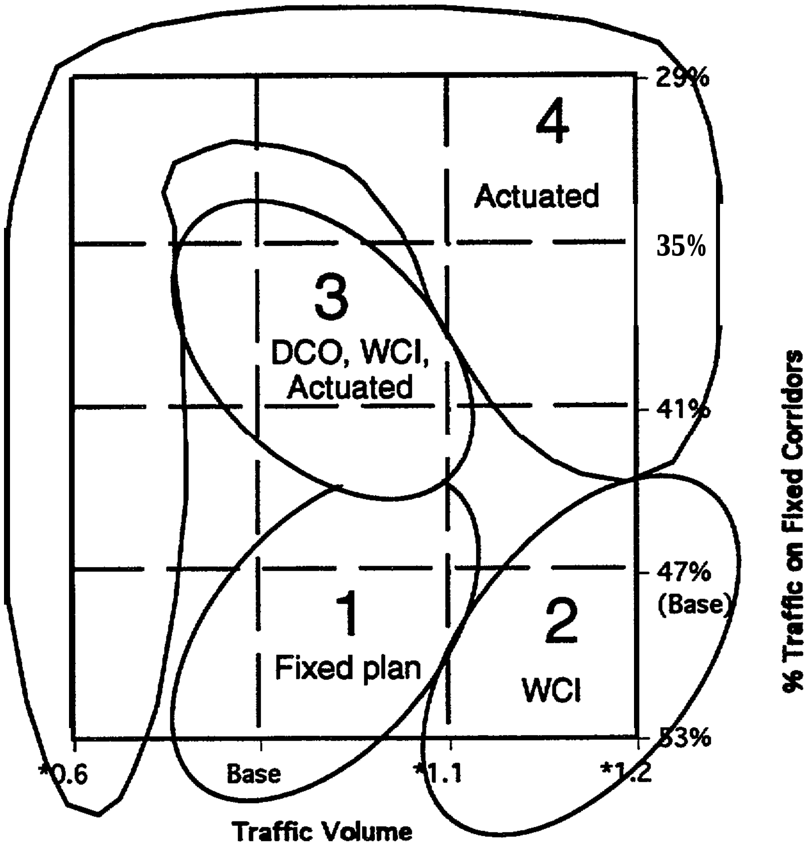

Figure 6-21. Best Adaptive Signal Strategy for Each Scenario

- In region 1, where traffic volumes and directions are about as expected, all adaptive signals result in travel time reductions of less than 5%. A good fixed plan performs just as well without extra expenditure. Actuated signals perform worse than fixed signals.
- In region 2, where traffic is heavier than expected but still conforms to pre-synchronized corridors, isolated signal optimization is the best adaptive strategy, providing 3-7% improvement over the fixed plan. Again, actuated signals perform worse than fixed signals.

- In region 3, all three adaptive strategies provide an improvement over the fixed plan, ranging from 5 to 15% reduction in average travel time. Dynamic corridor optimization performed slightly better than the other two strategies in this region.
- In region 4, consisting of all the scenarios with lighter than expected traffic and most. scenarios with a small proportion of traffic on pre-synchronized corridors, actuated signals provide the best performance, ranging from 15 to 25% reduction in average travel time.

The Architecture Team notes in the ITS Architecture Implementation Plan (Loral, 1995) that surges of traffic from special events was a significant factor for three cities that implemented ATMS on a large scale (Los Angeles, San Jose, and Anaheim). The methodology used for this report is one way of quantifying the advantage of ATMS for those conditions.

6.9.4 Caveats

The primary purpose of this study was to examine the potential benefits of various adaptive traffic control schemes under unexpected traffic conditions. In order to support more accurate estimates of the benefits of these schemes, further work will be necessary to quantify the extent to which such demand shifts are commonly present in traffic networks today.

The operation of all the adaptive signal control strategies depends heavily on detectors to provide real-time traffic counts to the signal controllers. In addition, the actuated signal controllers and the one of the corridor optimization schemes depend on knowing queue lengths as well as traffic counts. For the purposes of this study, the infrastructure necessary to install and operate detectors was assumed to be in place.

Optimization of urban traffic flows cannot be achieved by these signal control strategies alone. Certain intersections must provide for turning traffic, especially left-turning traffic, with turn pocket lanes and protected turn arrows. The current studies have not explored this issue.

Mitretek did not run a scenario where the majority of intersections had V/C ratios greater than one (an oversaturated network). This question may be pursued further in follow-on studies.